Dynamische virtuelle Kraftwerke zum Betrieb regenerativer Energiesysteme in aktiven Verteilnetzen

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FGW

htw Hochschule für Technik und Wirtschaft Berlin

University of Applied Sciences

Overview

1. Motivation
2. Problem Formulation
3. Model Reference Controller (MRC) Design
4. MRC Design for Solar Photovoltaic Systems
5. Experimental Consideration on HTW Test bed System
6. Conclusion
7. Literature

1. Motivation

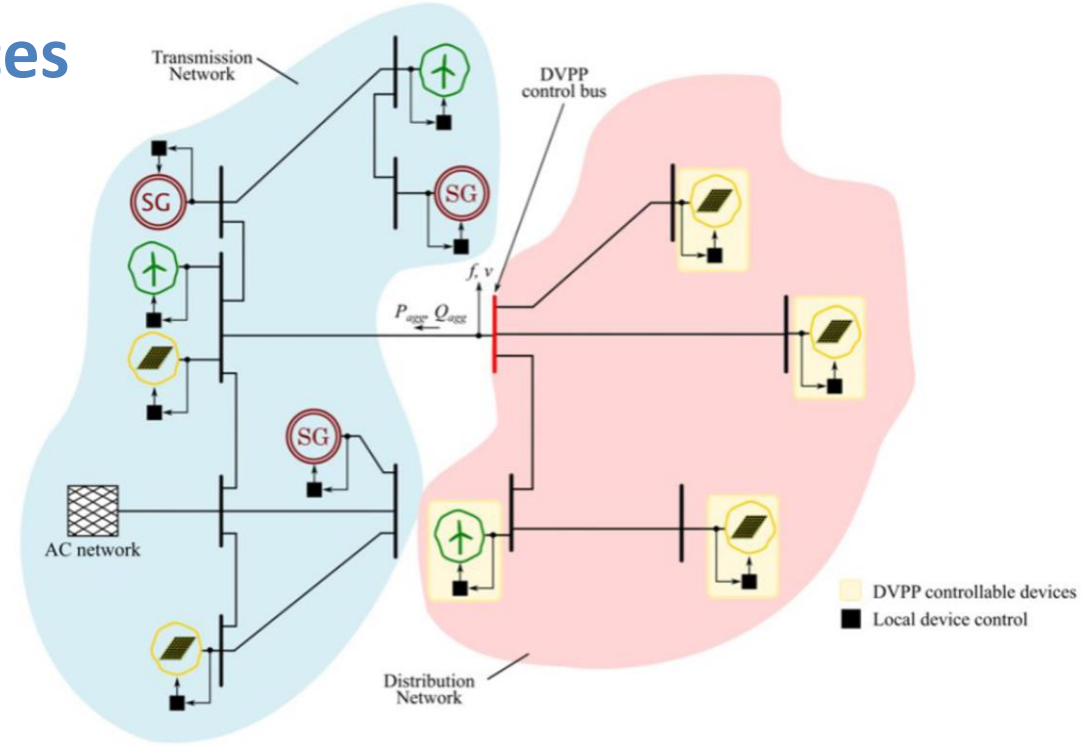
Aggregation of Distributed Energy Resources

- Aggregation of Distributed Resources by Dynamic Virtual Power Plants (DVPP)

  – Spatially distributed power plants are combined to one virtual power plant

  – In contrast to conventional VPPs, dynamic operations such as instantaneous reserve and virtual inertia are provided

  – So far, three different generic structures of DVPPs systems have been investigated



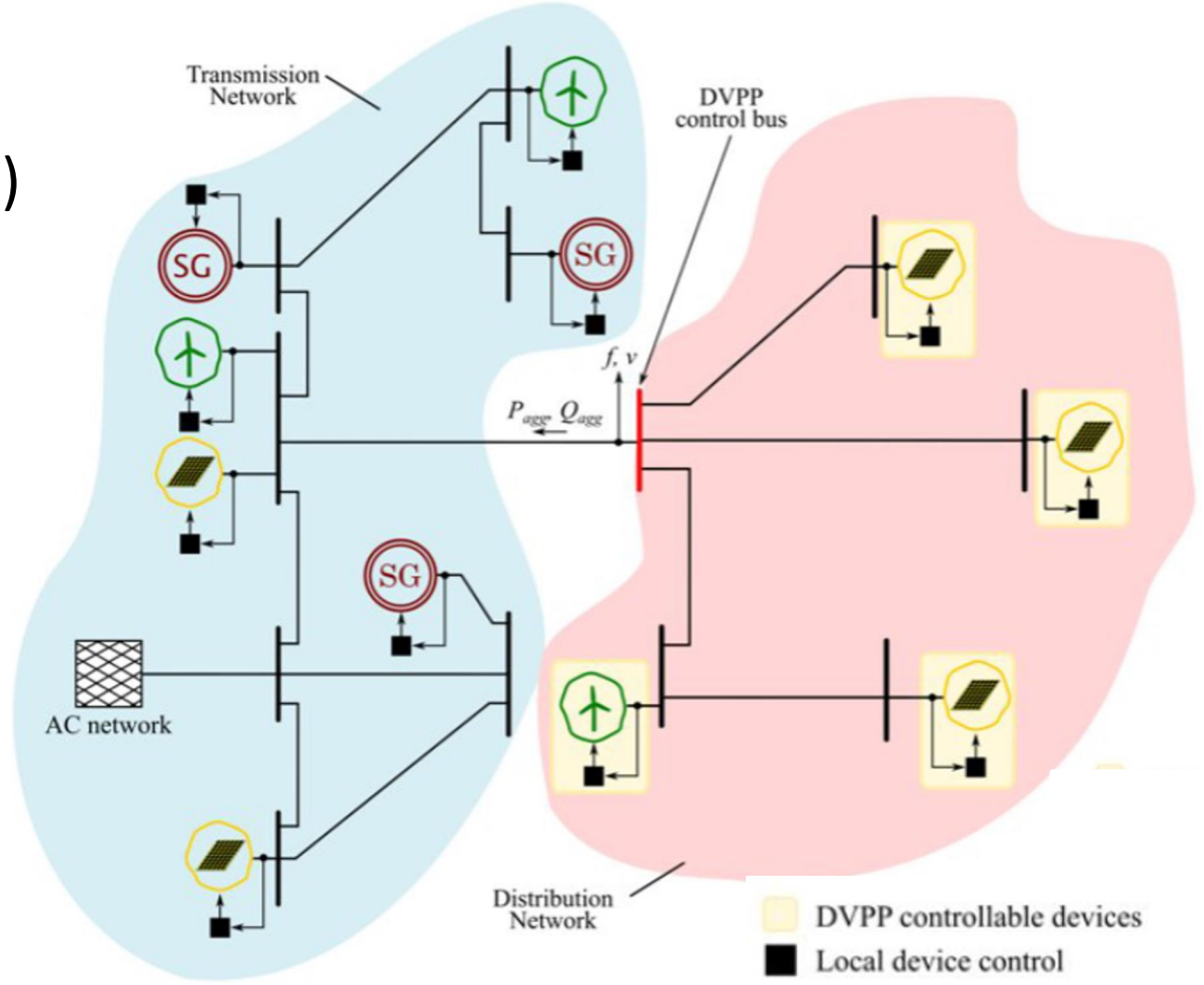
1. Motivation

Decentralized Control Scheme

- Dynamic Virtual Power Plant (DVPP)

CASE a)

DVPP is in a distribution grid that has <u>all devices under control</u>



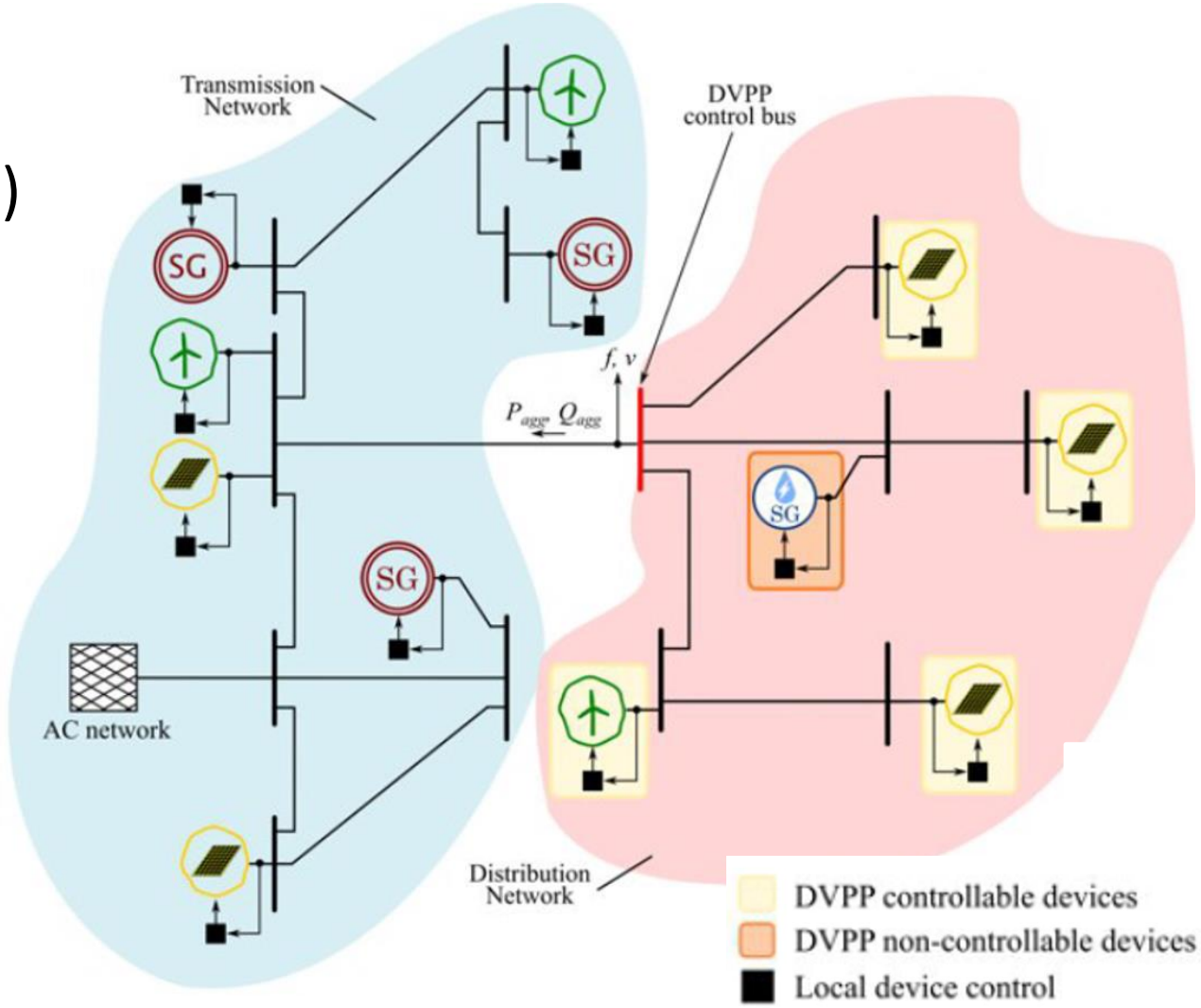
1. Motivation

Decentralized Control Scheme

- Dynamic Virtual Power Plant (DVPP)

CASE b)

DVPP is in a distribution grid with incorporating non-controllable devices



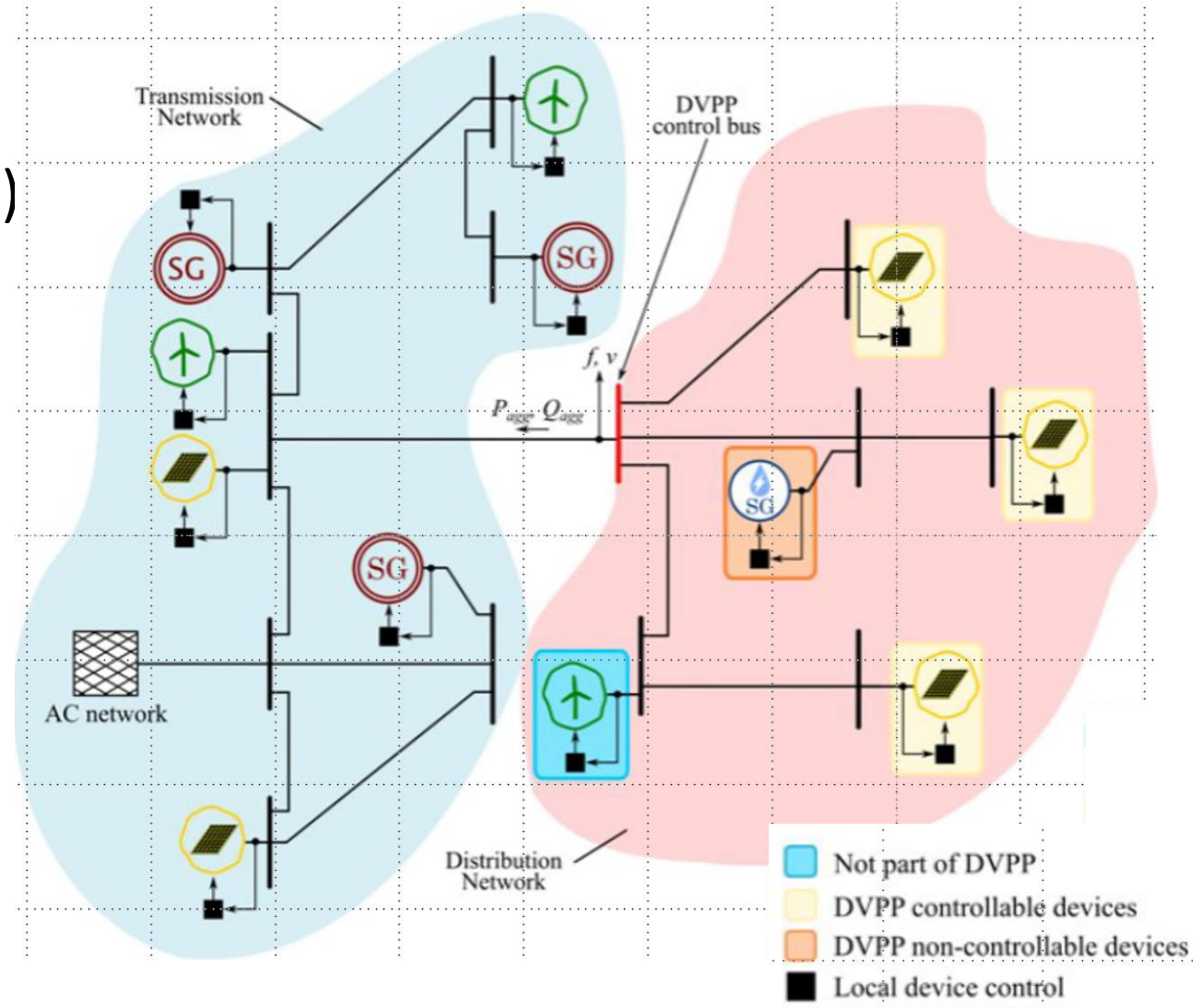
1. Motivation

Decentralized Control Scheme

- Dynamic Virtual Power Plant (DVPP)

CASE c)

DVPP is in a distribution grid with incorporating non-controllable devices AND <u>other generator units controlled by third parties</u>

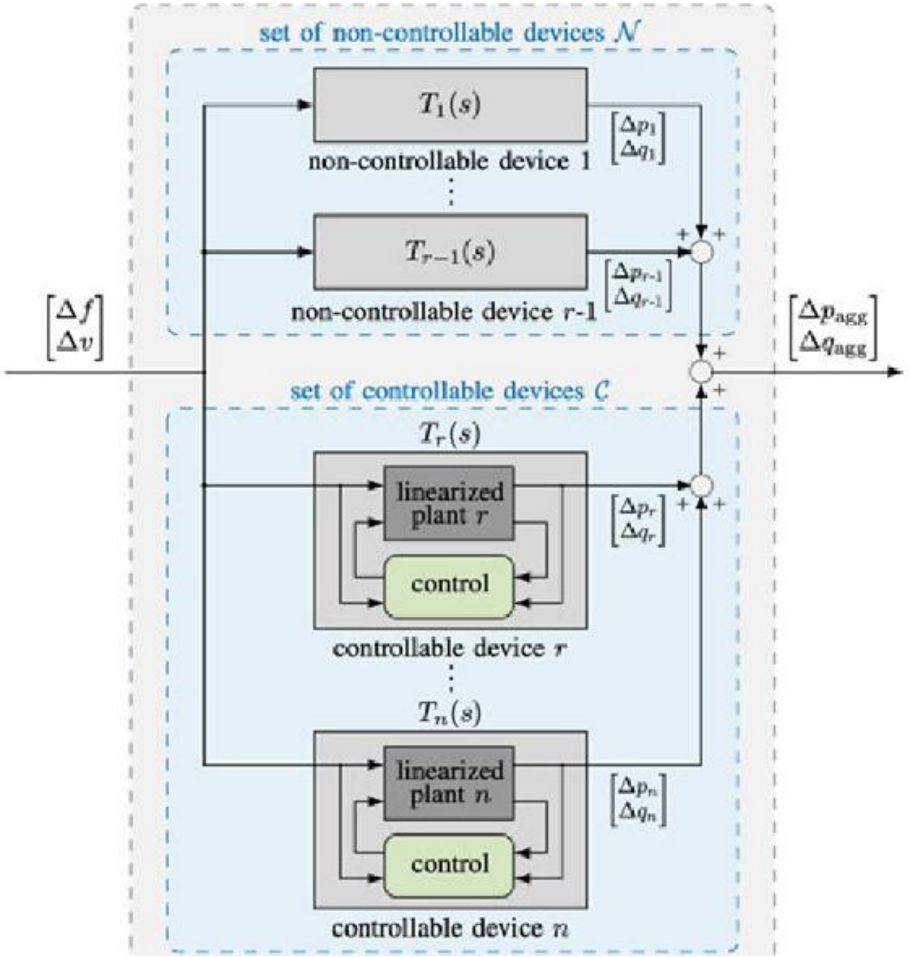


1. Motivation

Recent DVPP research results (H2020 Project POSYTYF)

https://posytyf-h2020.eu/

- Design of generic scenarios for DVPP assessment
- Basic concept of aggregation of individual power plants for grid control in DVPP and disaggregation into local reference models
- Local Model Reference Controller design for PV, Wind power plants and Battery Energy Storages



1. Motivation

Current research questions that are being addressed

- Transferring the DVPP concept to specific systems → Active Distribution Grids
- Integration of controllable loads as part of DVPP concept
- Systematic local controller design even at generator/inverter-based level

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Current research questions that are being addressed

- Transferring the DVPP concept to specific systems → Active Distribution Grids
- Integration of controllable loads as part of DVPP concept
- Systematic local controller design even at generator/inverter-based level
- Consideration of the non-linearities of regenerative energy systems
  - → Model reference control by polytopic systems which include nonlinearities
  - → Photovoltaic and Wind Turbine Systems with Instantaneous reserve
  - → Curtailed/deloading mode for positive “inertia”
  - → Adaptive Participation of local generators (take resource fluctuation into account)

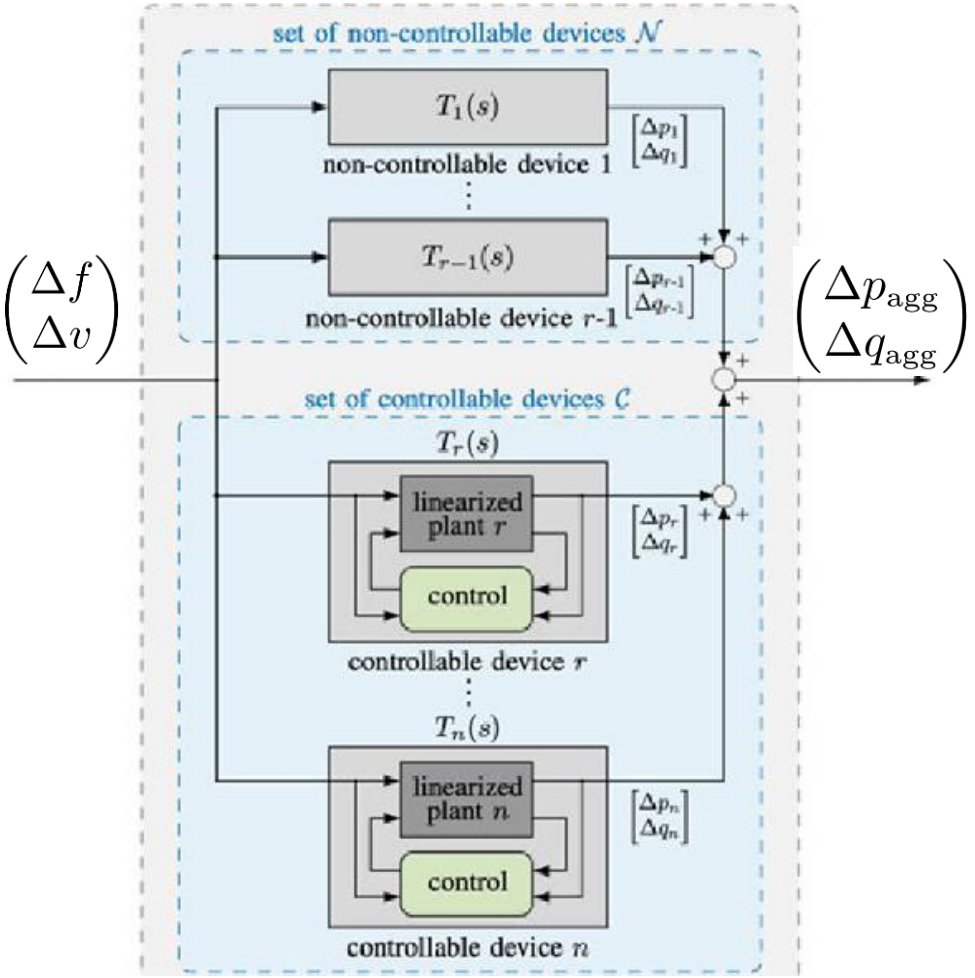
Formalization of Decentralized Control Problem

- Aggregated DVPP Reference Model

$$\begin{pmatrix} \Delta p_{\mathrm{agg}} \\ \Delta q_{\mathrm{agg}} \end{pmatrix} = T_{\mathrm{agg,ref}}(s) \begin{pmatrix} \Delta f \\ \Delta v \end{pmatrix}$$

$$T_{\mathrm{agg,ref}}(s) = \begin{pmatrix} T_{\mathrm{agg},11,\mathrm{ref}}(s) & T_{\mathrm{agg},12,\mathrm{ref}}(s) \\ T_{\mathrm{agg},21,\mathrm{ref}}(s) & T_{\mathrm{agg},22,\mathrm{ref}}(s) \end{pmatrix}$$

$$\Delta p_{\mathrm{agg}} = \sum_{i=1}^{N_p} \Delta p_i \,, \quad \Delta q_{\mathrm{agg}} = \sum_{i=1}^{N_p} \Delta q_i$$



Formalization of Decentralized Control Problem

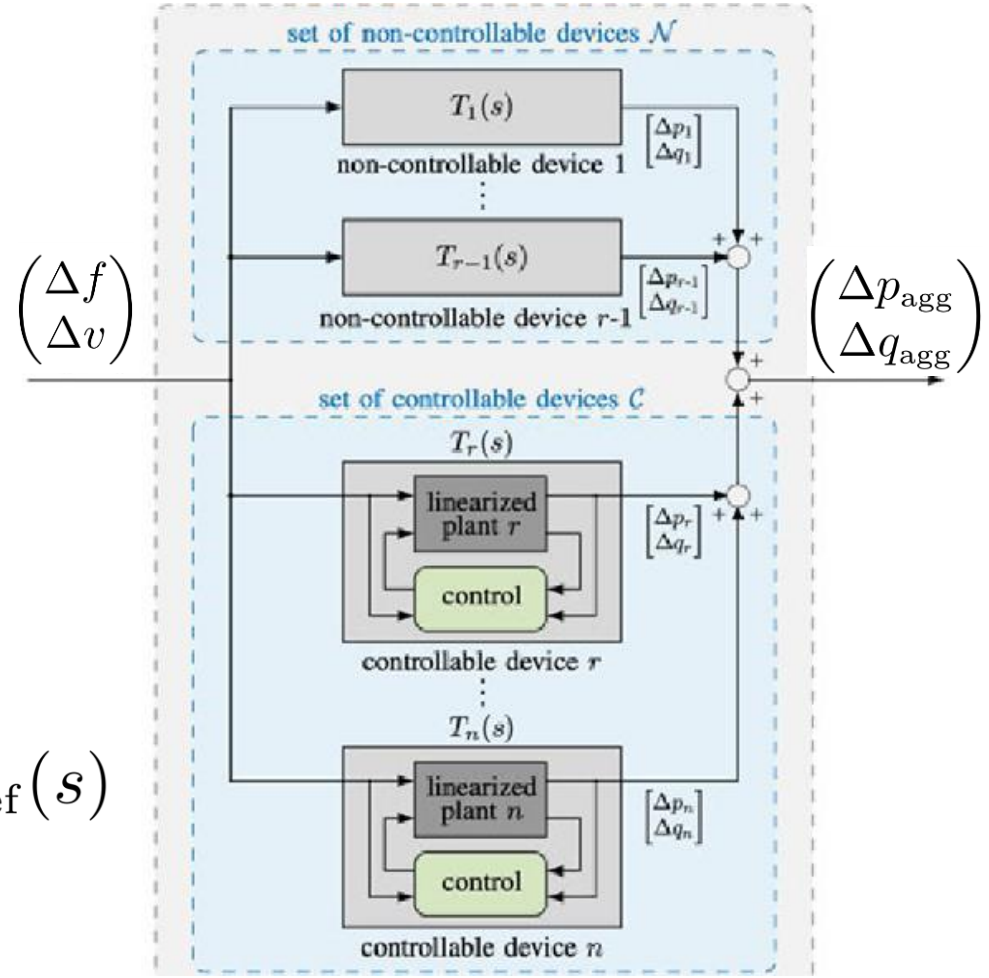
- Disaggregation of DVPP Reference Model

$$\begin{pmatrix}\Delta p_{\mathrm{agg}}\\ \Delta q_{\mathrm{agg}}\end{pmatrix} = \underbrace{\sum_{i=1}^{N_p} T_{\mathrm{i,ref}}(s)}_{T_{\mathrm{agg,ref}}(s)} \begin{pmatrix}\Delta f\\ \Delta v\end{pmatrix}$$

- Introducing the dynamic participation matrix

  we get

$$T_{\mathrm{agg,ref}}(s) = \sum_{i=1}^{N_p} M_i(s)\, T_{\mathrm{agg,ref}}(s) = \sum_{i=1}^{N_p} T_{\mathrm{i,ref}}(s)$$



Formalization of Decentralized Control Problem

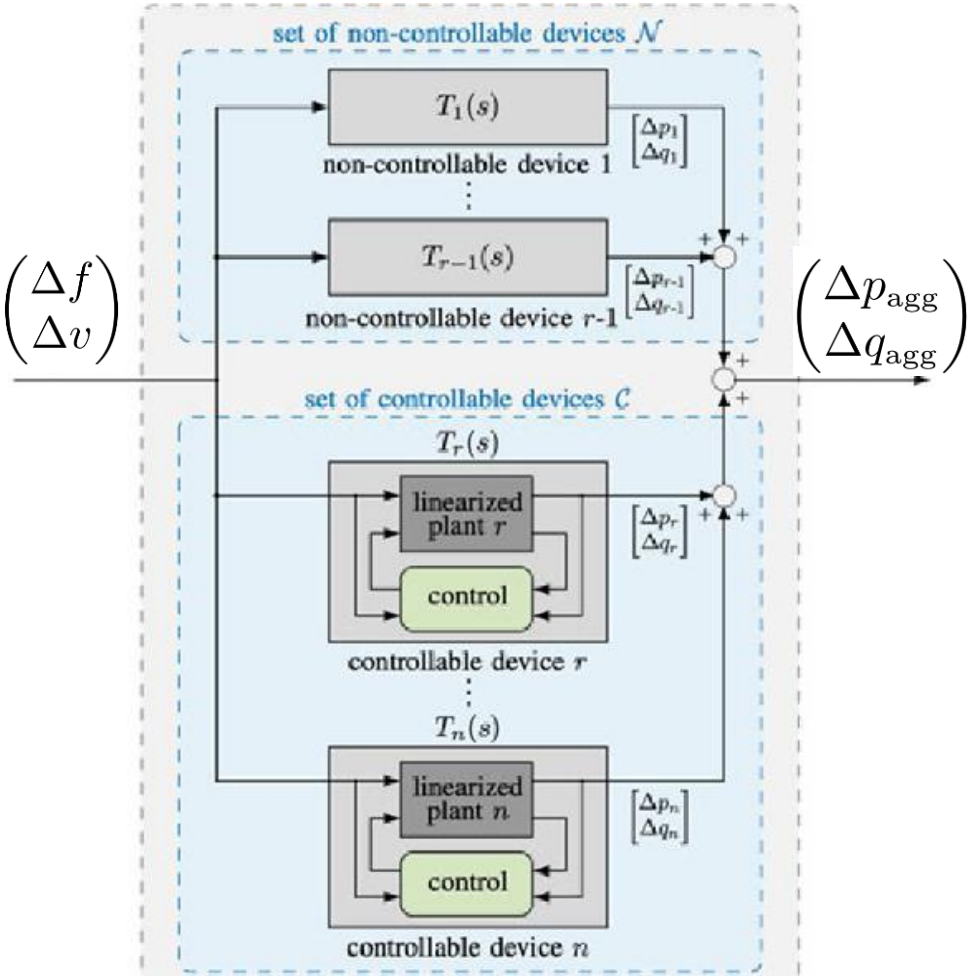
- This results in reference models for local design

$$\begin{pmatrix} \Delta p_\mathrm{i} \\ \Delta q_\mathrm{i} \end{pmatrix} = T_{\mathrm{i,ref}}(s) \begin{pmatrix} \Delta f \\ \Delta v \end{pmatrix}$$

- Ref. model can be realized in state space form

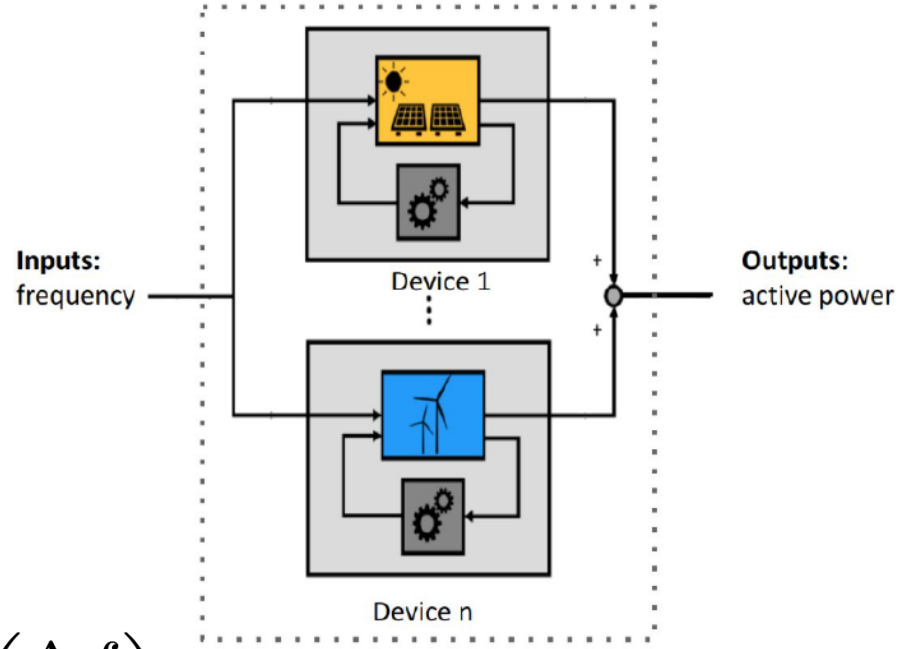
$$\dot{\boldsymbol{x}}^\mathrm{r} = \mathbf{A}^\mathrm{r}\boldsymbol{x}^\mathrm{r} + \mathbf{E}^\mathrm{r}\boldsymbol{w} \qquad \mathbf{y} = \begin{pmatrix} \Delta p_\mathrm{i} \\ \Delta q_\mathrm{i} \end{pmatrix}, \ \mathbf{w} = \begin{pmatrix} \Delta f \\ \Delta v \end{pmatrix}$$
$$\boldsymbol{y}^\mathrm{r} = \mathbf{C}^\mathrm{r}\boldsymbol{x}^\mathrm{r} + \mathbf{F}^\mathrm{r}\boldsymbol{w}$$

and will be used later



Frequency Control Problem

- Assumptions:
  - Decoupling of frequency and voltage control by p and q injection
  - Common frequency measurement point and distributed power production

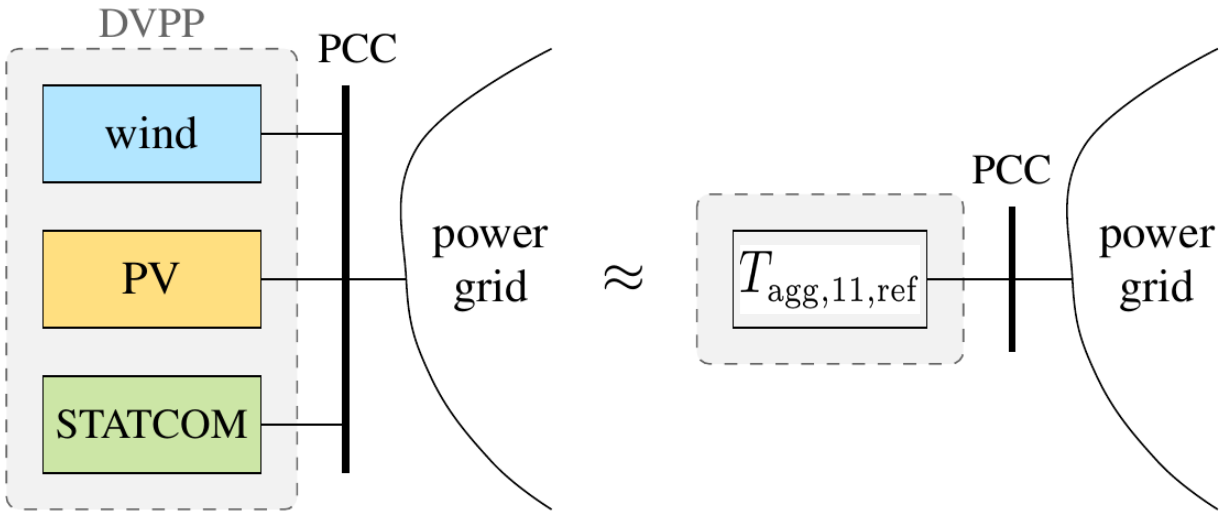


$$\begin{pmatrix} \Delta p_{\mathrm{agg}} \\ \Delta q_{\mathrm{agg}} \end{pmatrix} = \begin{pmatrix} T_{\mathrm{agg},11,\mathrm{ref}}(s) & 0 \\ 0 & T_{\mathrm{agg},22,\mathrm{ref}}(s) \end{pmatrix} \begin{pmatrix} \Delta f \\ \Delta v \end{pmatrix}$$

$$\Delta p_{\mathrm{agg}} = \sum_{i=1}^{N_p} \Delta p_i = \sum_{i=1}^{N_p} T_{\mathrm{i},11,\mathrm{ref}}(s) \Delta f = \sum_{i=1}^{N_p} m_i(s)\, T_{\mathrm{agg},11,\mathrm{ref}}(s) \Delta f$$

Frequency Control Problem

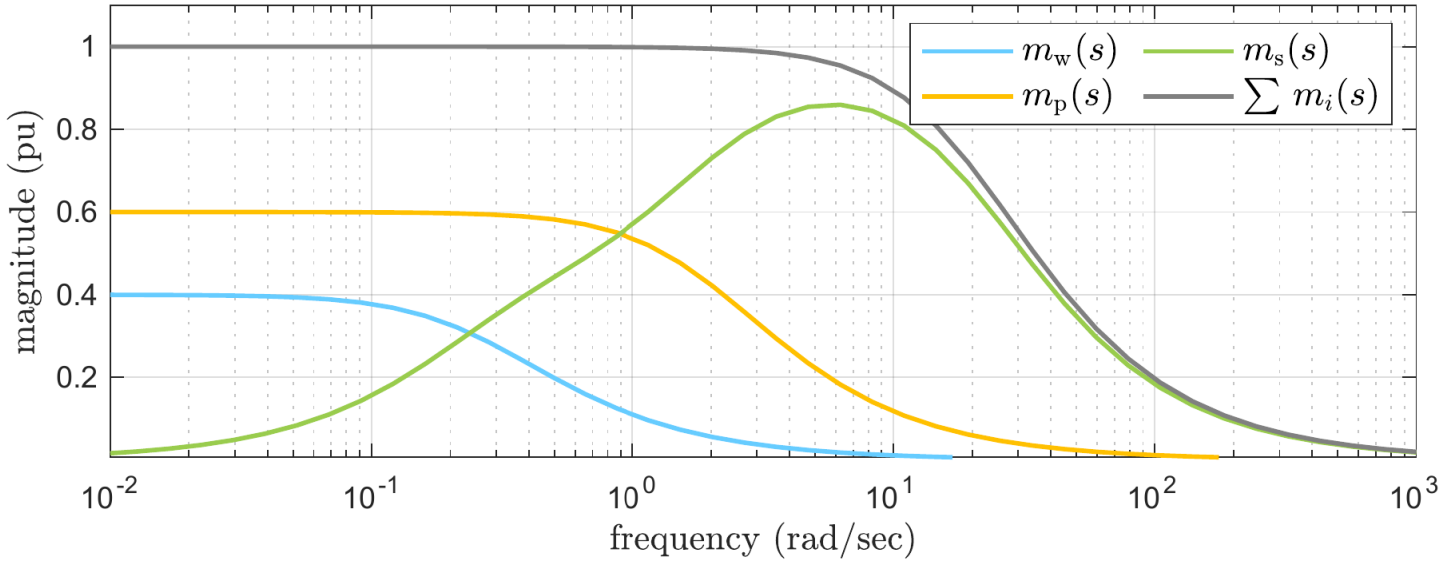
- Illustrating Example
  - DVPP contains three power plants with different power injection dynamics
  - Due to physical limitations, the dynamics of the closed control loop/reference models of the power plant types can significantly differ



$$\Delta p_{\mathrm{agg}}(s) = \underbrace{\frac{-D}{\tau s + 1}}_{= T_{\mathrm{agg},11,\mathrm{ref}}(s)} \Delta f(s)$$

Frequency Control Problem

- Illustrating Example
  - Taken into account the power plant constraints by dynamic participation factors



$$m_{\mathrm{w}}(s) = \frac{\mu_{\mathrm{w}}}{\tau_{\mathrm{w}} s + 1}, \qquad m_{\mathrm{p}}(s) = \frac{\mu_{\mathrm{p}}}{\tau_{\mathrm{p}} s + 1}$$

ideal sum condition $\sum_{i \in \{w,p,s\}} m_i(s) = 1$

$$m_s(s) = 1 - m_w(s) - m_p(s)$$

Frequency Control Problem

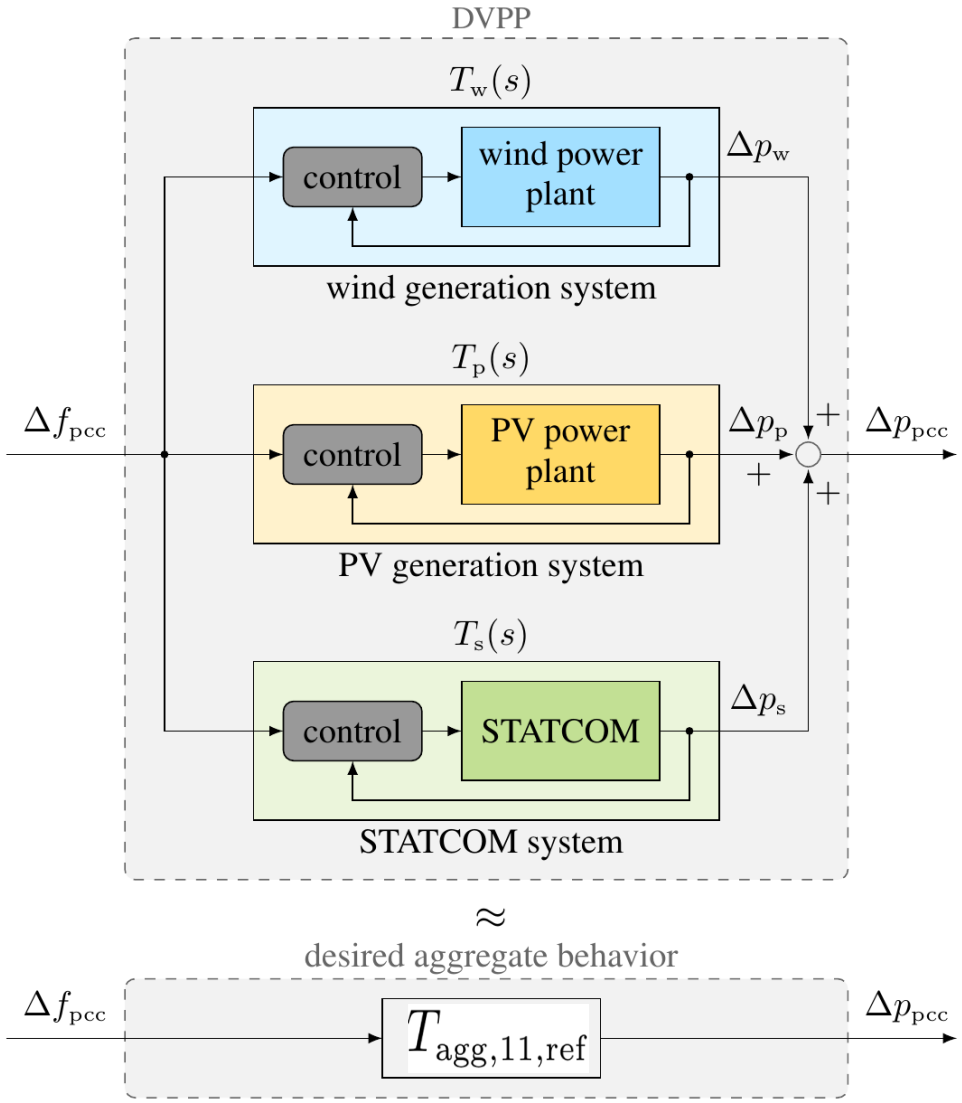
- Illustrating Example

  Local Model Reference controller design based on the disaggregated $T_{\mathrm{agg},11,\mathrm{ref}}$

$$T_{\mathrm{i},11,\mathrm{ref}}(s) = m_i(s)\, T_{\mathrm{agg},11,\mathrm{ref}}(s)$$

$$\Delta p_i = T_{\mathrm{i},11,\mathrm{ref}}(s)\Delta f \qquad \Delta p_{\mathrm{pcc}} \stackrel{!}{=} \Delta p_{\mathrm{agg}} = \sum_{i\in\{w,p,s\}} \Delta p_i$$

$$T_{\mathrm{w}} := T_{\mathrm{w},11,\mathrm{ref}},\ T_{\mathrm{p}} := T_{\mathrm{p},11,\mathrm{ref}},\ T_{\mathrm{s}} := T_{\mathrm{s},11,\mathrm{ref}}$$



3. Local Model Reference Controller Design

Problem Formulation → Reference Model from Disaggregation $\begin{pmatrix}\Delta p_\mathrm{i}\\ \Delta q_\mathrm{i}\end{pmatrix} = T_{\mathrm{i,ref}}(s)\begin{pmatrix}\Delta f\\ \Delta v\end{pmatrix}$

- Reference Model in State Space form $\dot{\boldsymbol{x}}^\mathrm{r} = \mathbf{A}^\mathrm{r}\boldsymbol{x}^\mathrm{r} + \mathbf{E}^\mathrm{r}\boldsymbol{w}$, $\boldsymbol{y}^\mathrm{r} = \mathbf{C}^\mathrm{r}\boldsymbol{x}^\mathrm{r} + \mathbf{F}^\mathrm{r}\boldsymbol{w}$
- Class of **Non-linear plant models** in Takagi-Sugeno form (Polytopic Model)

$$\dot{\boldsymbol{x}} = \sum_{i=1}^{N_r} h_i(\boldsymbol{z})\left(\mathbf{A}_i\boldsymbol{x} + \mathbf{B}_i u + \boldsymbol{a}_i\right) , \quad \boldsymbol{y} = \mathbf{C}\,\boldsymbol{x}$$

with the control input u, gain scheduling variable z (= x and/or u) and the output y

- **Motivation** using T-S models: Many power plant models like wind, hydro power plant show a strong nonlinear behavior

Problem Formulation

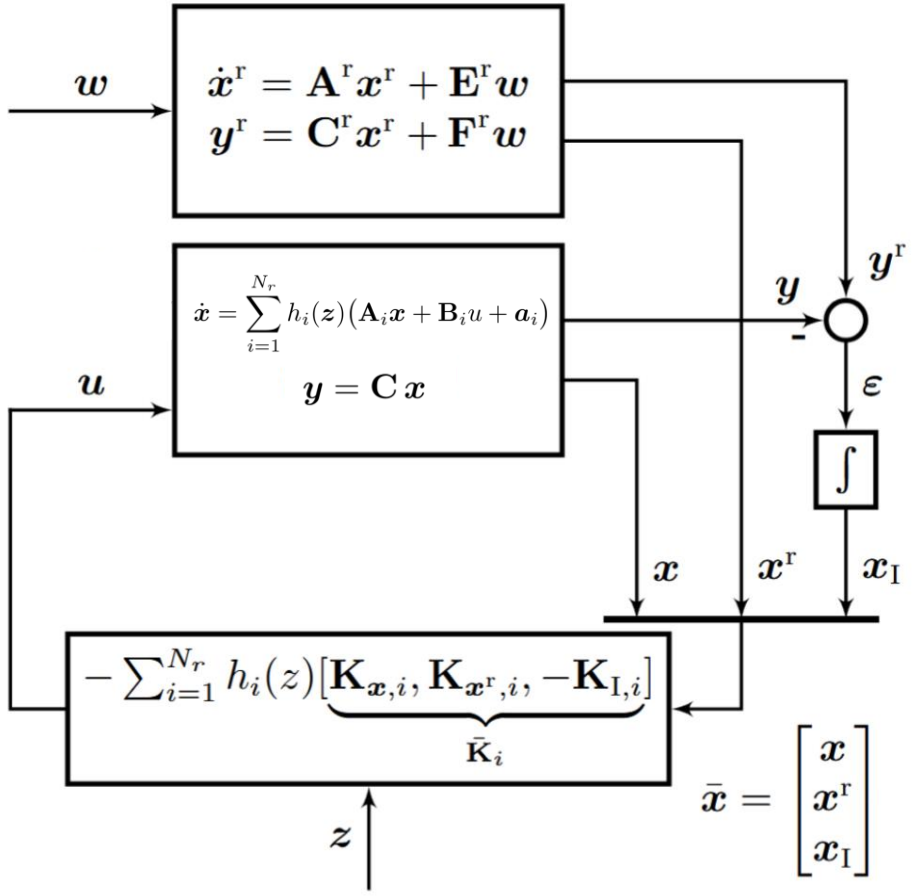
Control law

$$u = -\sum_{i=1}^{N_r} h_i(z) \underbrace{\begin{pmatrix} K_{x,i} & K_{x^r,i} & -K_{I,i} \end{pmatrix}}_{\bar{K}_i} \underbrace{\begin{pmatrix} x \\ x^r \\ x_I \end{pmatrix}}_{\bar{x}}$$

Augmented **Design Model**

$$\dot{\bar{x}} = \sum_{i=1}^{N_r} h_i(z) \underbrace{\begin{pmatrix} A_i & 0 & 0 \\ 0 & A^r & 0 \\ -C & C^r & 0 \end{pmatrix}}_{\bar{A}_i} \bar{x} + \sum_{i=1}^{N_r} h_i(z) \underbrace{\begin{pmatrix} B_i \\ 0 \\ 0 \end{pmatrix}}_{\bar{B}_i} u + \sum_{i=1}^{N_r} h_i(z) \underbrace{\begin{pmatrix} E_i \\ E_i^r \\ F^r - F_i \end{pmatrix}}_{\bar{E}_i} w,$$

$$\varepsilon = \underbrace{\begin{pmatrix} -C_i & C^r & 0 \end{pmatrix}}_{\bar{C}_i} \bar{x} + \underbrace{\begin{pmatrix} F^r - F_i \end{pmatrix}}_{\bar{F}_i} w \quad \text{with} \quad \varepsilon = \dot{x}_I = y^r - y$$



Problem Formulation

- Objective: minimize the input-to-output gain with respect to the input w and output ε:

$$\begin{aligned} &\text{minimize} && \gamma \\ &\text{subject to} && \sup_{\|w\|_2 \neq 0} \frac{\|\varepsilon\|_2}{\|w\|_2} \leq \gamma \end{aligned} \qquad \varepsilon = \dot{x}_I = y^r - y$$

- Controller coefficients are calculated by solving the LMI problem (Lyapunov-based and Hinf)

$$\Gamma_{ij} = \begin{pmatrix} \bar{A}_i X + X\bar{A}_i^T - \bar{B}_i \bar{M}_j - \bar{M}_j^T \bar{B}_i^T & \bar{E}_i & X\bar{C}_i^T \\ \bar{E}_i^T & -\gamma^2 I & \bar{F}_i^T \\ \bar{C}_i X & \bar{F}_i & -I \end{pmatrix} \prec 0 \quad , \quad X \succ 0$$

$$\text{for all } i, j = 1, \ldots, N_r \text{ s.t. } h_i \cdot h_j \neq 0$$

$$\tilde{K}_j = M_j X^{-1} \quad , \quad j = 1, 2, \ldots, N_r$$

Problem Formulation

- **Illustrating Mathematical Example**: Given a multivariable nonlinear model

$$\dot{x} = \begin{pmatrix} -\frac{1}{2}\cos\left(\frac{\pi}{20}x_1\right) & \frac{1}{4} \\ \frac{1}{3} & -\frac{4}{5} \end{pmatrix} x + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} u + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} w, \quad y = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} x$$

$$\text{with } x = (x_1, x_2)^T, w = (\Delta f, \Delta v)^T, \text{ and } y = (\Delta p, \Delta q)^T$$

- Objective: Controller is to be found, which should match the plant model to the reference model

$$\dot{x}^r = \begin{pmatrix} -\frac{1}{2} & 0 \\ 0 & -\frac{4}{5} \end{pmatrix} x^r + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} w, \quad y^r = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} x^r$$

Problem Formulation

- **Illustrating Mathematical Example:** In Takagi-Sugeno form by Sector-Nonlinear approach

→ Non-linear term in the plant model is bounded (min/max)

$$\min(f) = \cos\left(\frac{\pi}{20}\max(x_1)\right), \quad \max(f) = \cos\left(\frac{\pi}{20}0\right) = 1$$

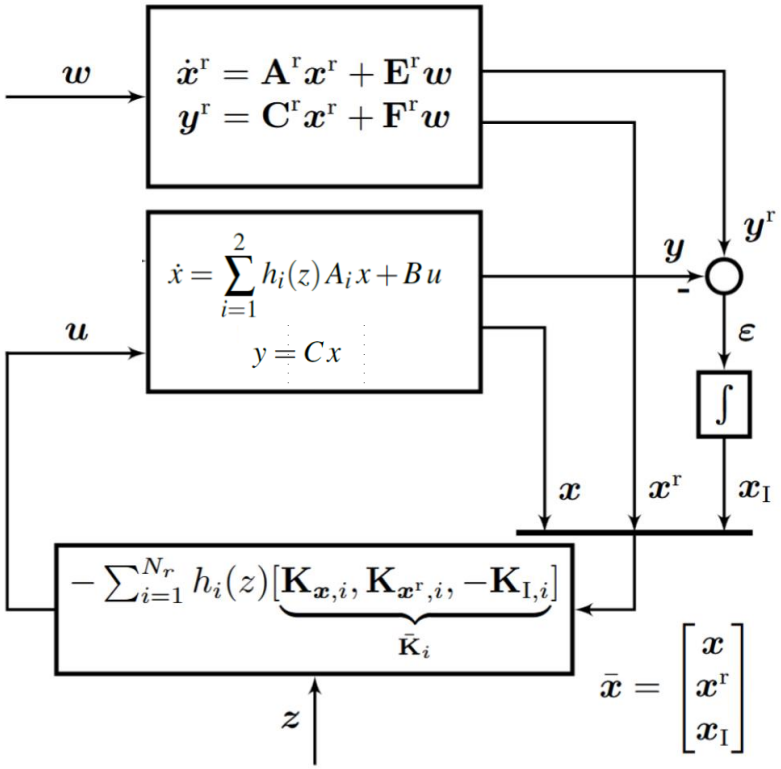
This gives an equivalent formulation $\dot{x} = \sum_{i=1}^{2} h_i(z) A_i x + B u, \qquad y = C x$

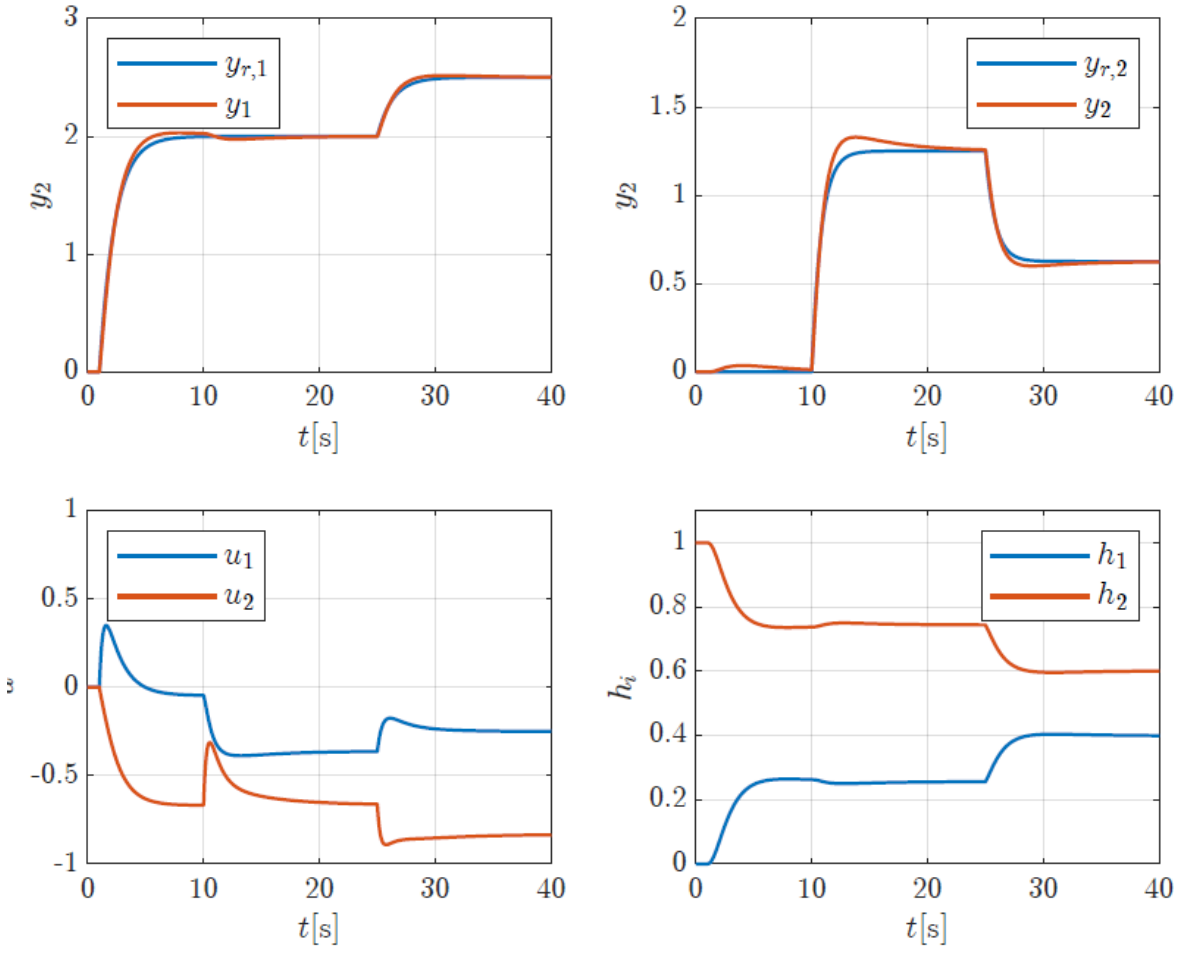
where $A_1 = \begin{pmatrix} -\frac{1}{2}\max(f) & \frac{1}{4} \\ \frac{1}{3} & -\frac{4}{5} \end{pmatrix}, \quad A_2 = \begin{pmatrix} -\frac{1}{2}\min(f) & \frac{1}{4} \\ \frac{1}{3} & -\frac{4}{5} \end{pmatrix}$

3. Local Model Reference Controller Design

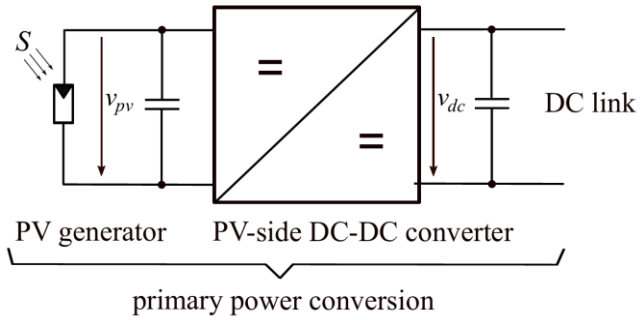
Problem Formulation

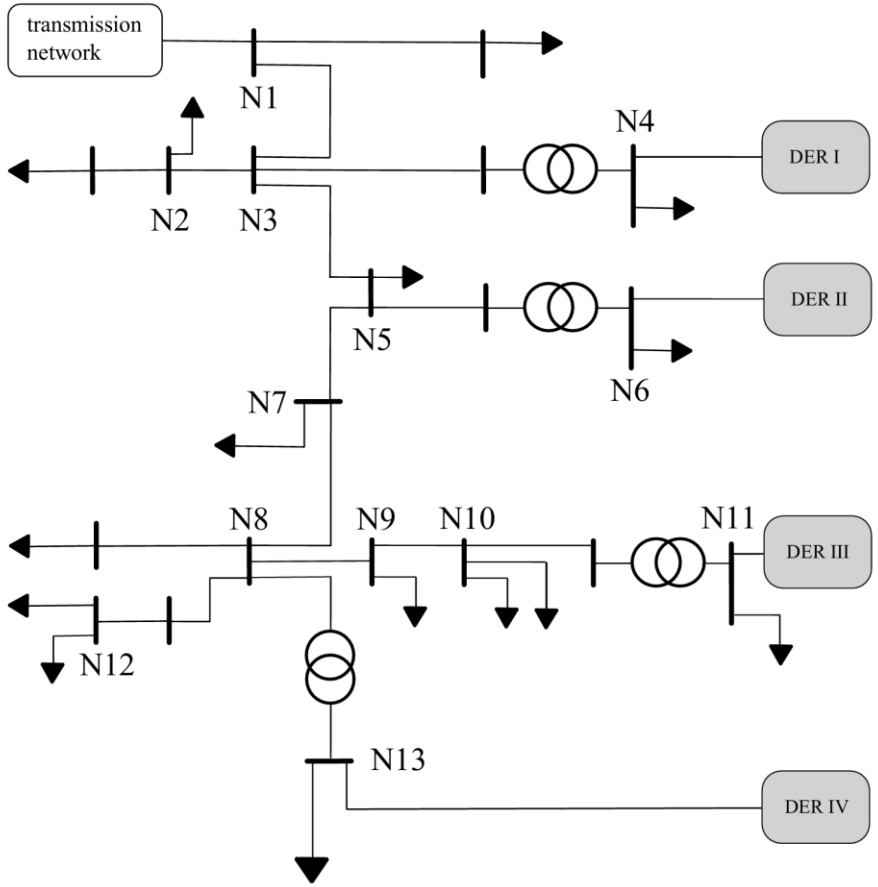
- **Illustrating Mathematical Example:**
  Simulation Results





Photovoltaic (PV) Plant Modelling: Example with Buck Converter





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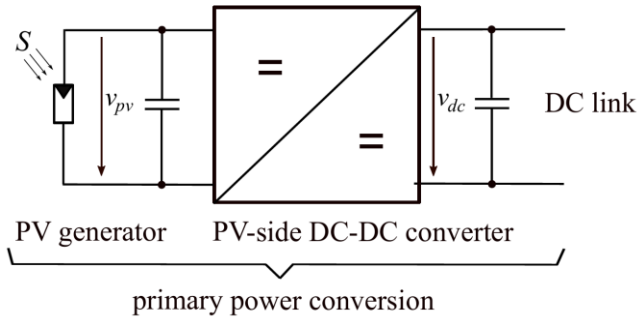


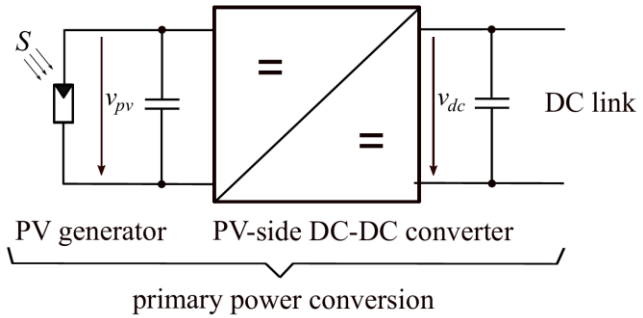
$$\dot{x}_1 = -\frac{1}{C}\, x_2\, u_1 + \frac{1}{C}\, f_{\mathrm{pv}}(x_1, S, T_{\mathrm{c}}) \;,$$

$$\dot{x}_2 = \frac{1}{L}\, x_1\, u_1 - \frac{1}{L}\, u_2 \;,$$

$$\boldsymbol{x} = [\, x_1 \,,\, x_2 \,]^{\top} = [\, v_{\mathrm{pv}} \,,\, i_{\mathrm{L}} \,]^{\top} \qquad \boldsymbol{u} = [\, u_1 \,,\, u_2 \,]^{\top} = [\, d \,,\, v_{\mathrm{dc}} \,]^{\top}$$

Note, the controllable input is the duty cycle d

Photovoltaic (PV) Plant Modelling: Example with Buck Converter



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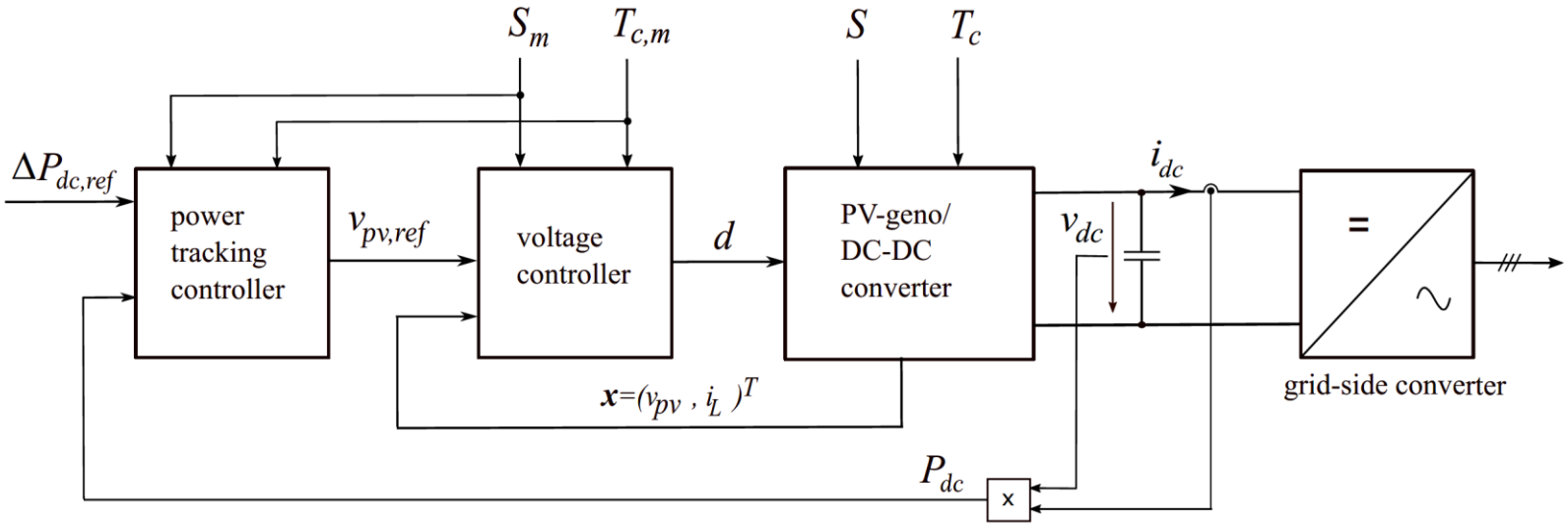
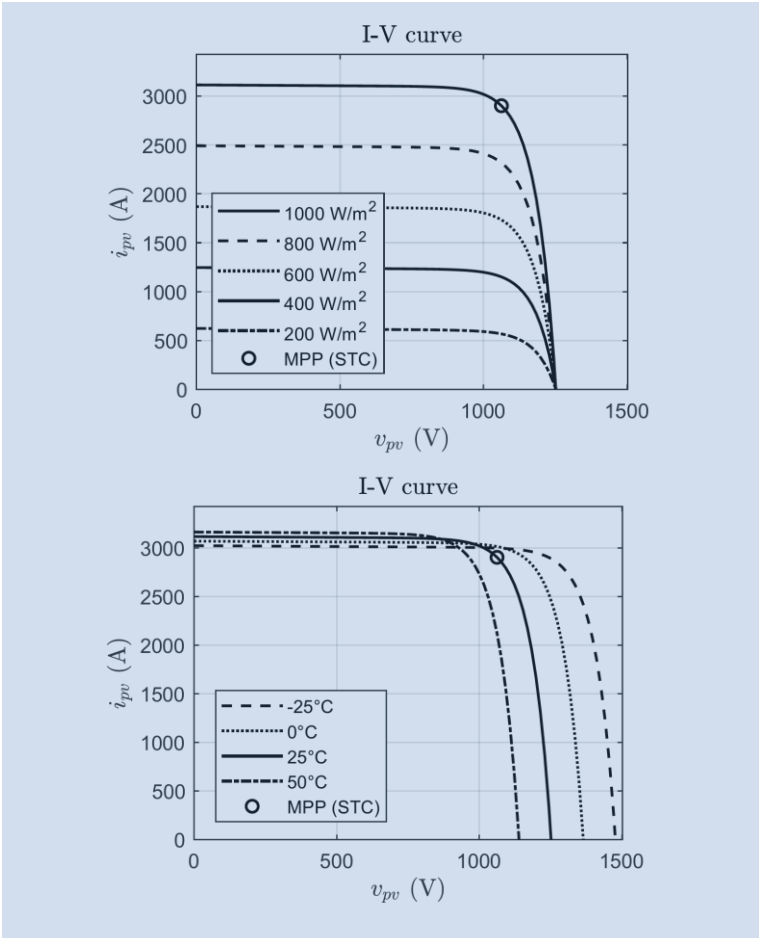


4. Model Reference Controller Design for Solar Photovoltaic Systems

Photovoltaic (PV) Plant Modelling: Example with Buck Converter



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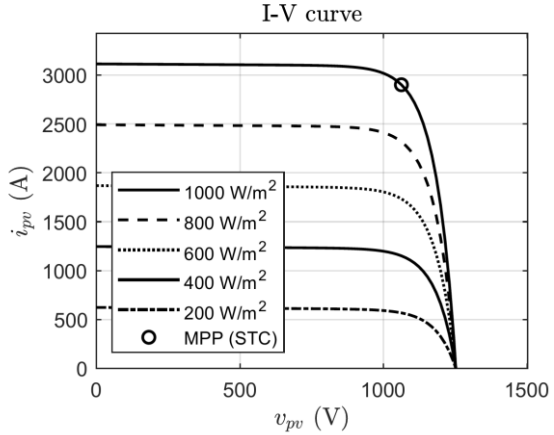
Photovoltaic (PV) Plant Modelling



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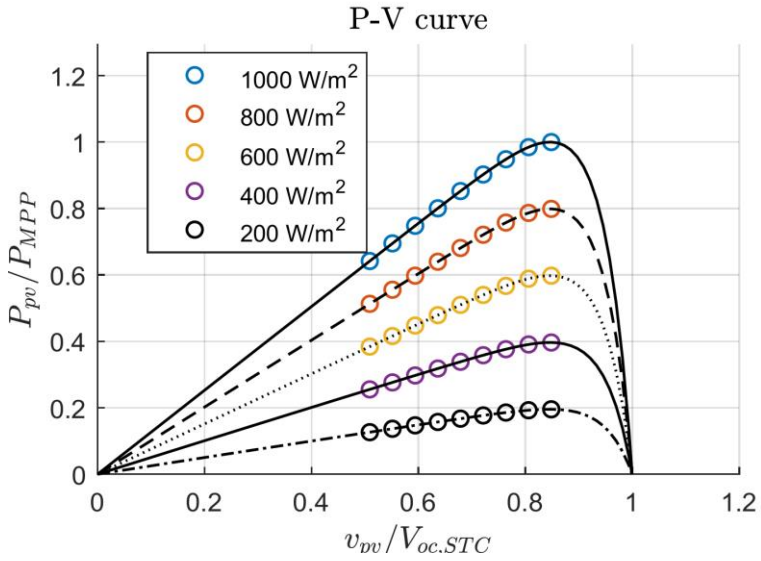


$$\dot{\boldsymbol{x}} = \mathbf{A}_i \boldsymbol{x} + \mathbf{B}_i u \underbrace{-\mathbf{A}_i \boldsymbol{x}_i^e - \mathbf{B}_i u_i^e}_{\boldsymbol{a}_i}$$

$$v_{\mathrm{pv}}^e = z_1^e = \{0.60,\, 0.65,\, \ldots,\, 0.95,\, 1.00\} \cdot v_{\mathrm{pv,MPP}}$$
$$S^e = z_2^e = \{200,\, 400,\, 600,\, 800,\, 1000\}\,,$$
$$T_{\mathrm{c}}^e = z_3^e = \{273,\, 298,\, 323\}\,,$$

$$\dot{\boldsymbol{x}} = \sum_{i=1}^{N_r} h_i(\boldsymbol{z}) \left(\mathbf{A}_i \boldsymbol{x} + \mathbf{B}_i u + \boldsymbol{a}_i \right)$$

Photovoltaic (PV) Plant Modelling

- Local linear models

  Related to equilibrium points

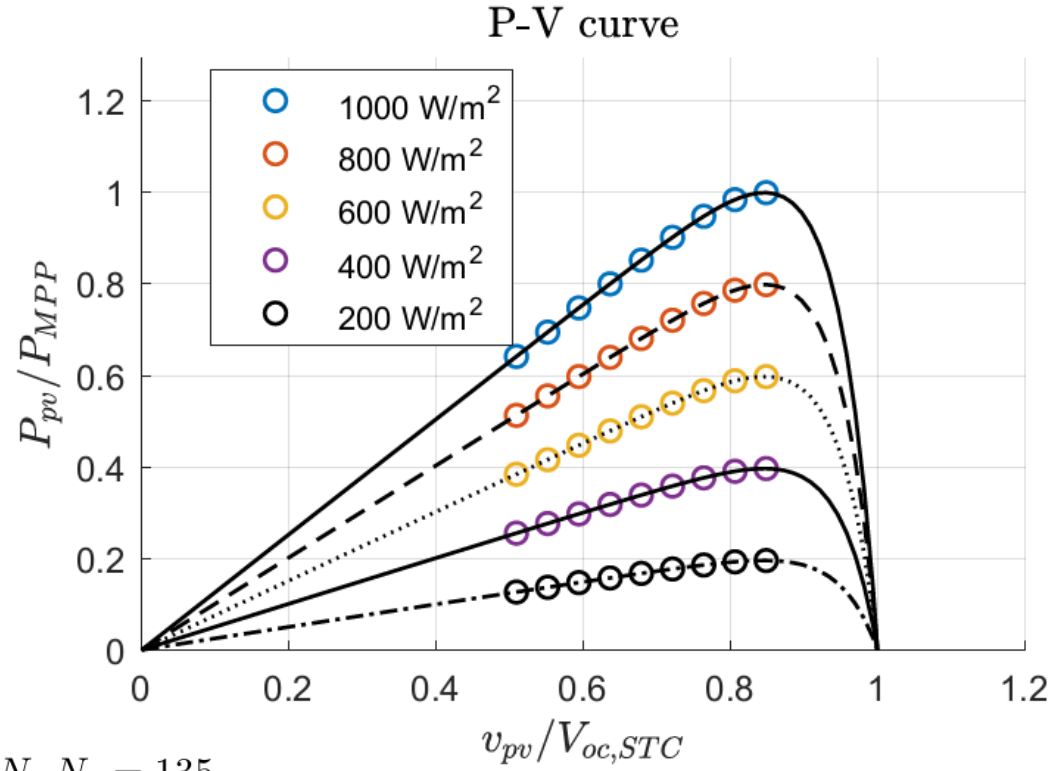
  of the nonlinear PV model

$$\sum_{i=1}^{N_r} h_i(\boldsymbol{z}) = \prod_{j=1}^{N_l} \sum_{k=1}^{N_j} w_{k,j}(z_j) = 1\,, \quad N_r = \prod_{j=1}^{N_l} N_j$$

$$z_1 = x_1,\ z_2 = S \text{ and } z_3 = T_\mathrm{c}$$

$$v_\mathrm{pv}^e = z_1^e = \{0.60,\ 0.65,\ \ldots,\ 0.95,\ 1.00\} \cdot v_\mathrm{pv,MPP},$$
$$S^e = z_2^e = \{200,\ 400,\ 600,\ 800,\ 1000\},$$
$$T_\mathrm{c}^e = z_3^e = \{273,\ 298,\ 323\},$$

which results in the total number of local models $N_r = N_1\, N_2\, N_3 = 135$



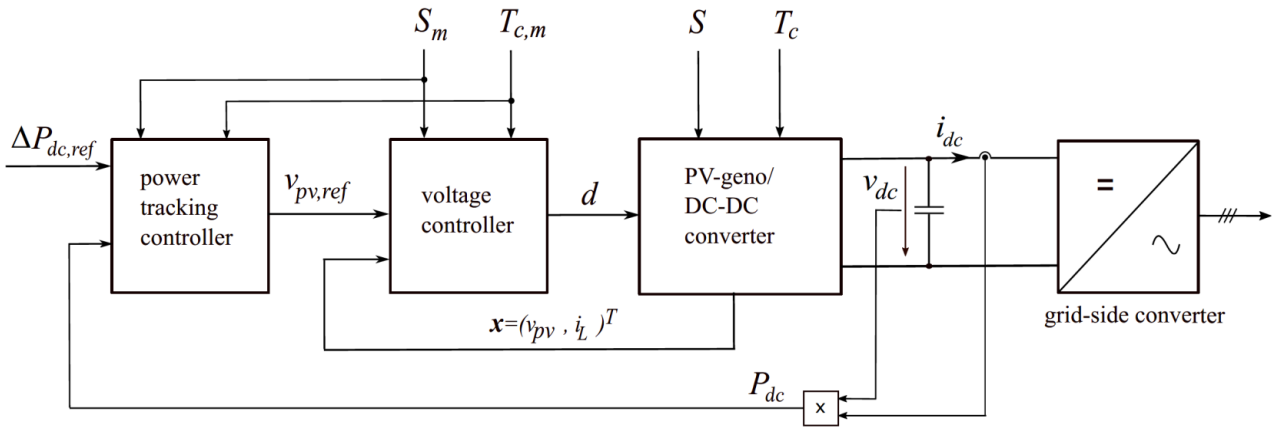
4. Model Reference Controller Design for Solar Photovoltaic Systems

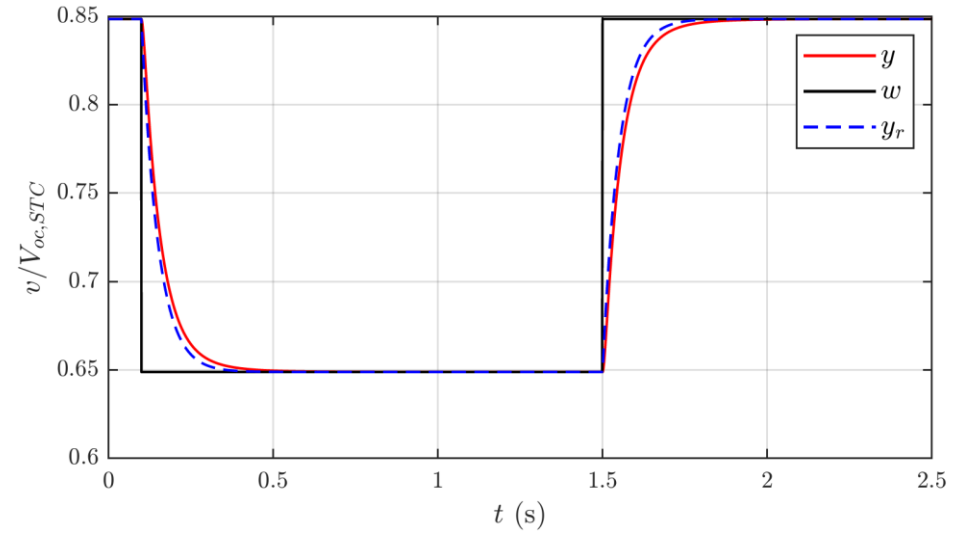
Reference Model

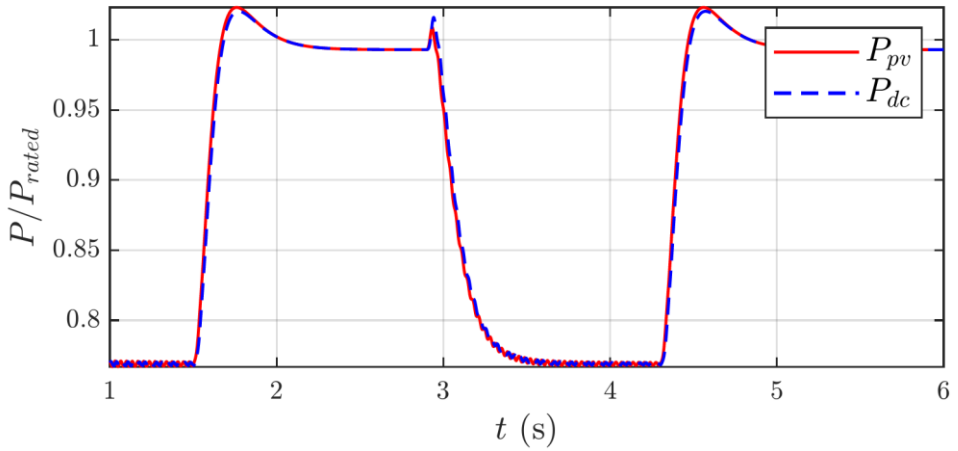
$$\dot{\boldsymbol{x}}^{\mathrm{r}} = \underbrace{\begin{bmatrix} -\frac{1}{\tau_{\mathrm{pv}}} & 0 \\ 0 & -\frac{1}{\tau_L} \end{bmatrix}}_{\mathbf{A}^{\mathrm{r}}} \boldsymbol{x}^{\mathrm{r}} + \underbrace{\begin{bmatrix} \frac{1}{\tau_{\mathrm{pv}}} & 0 \\ 0 & \frac{1}{\tau_L} \end{bmatrix}}_{\mathbf{E}^{\mathrm{r}}} \boldsymbol{w}$$

$$\tau_{pv} = 0.05$$

$$\tau_L = 0.1$$

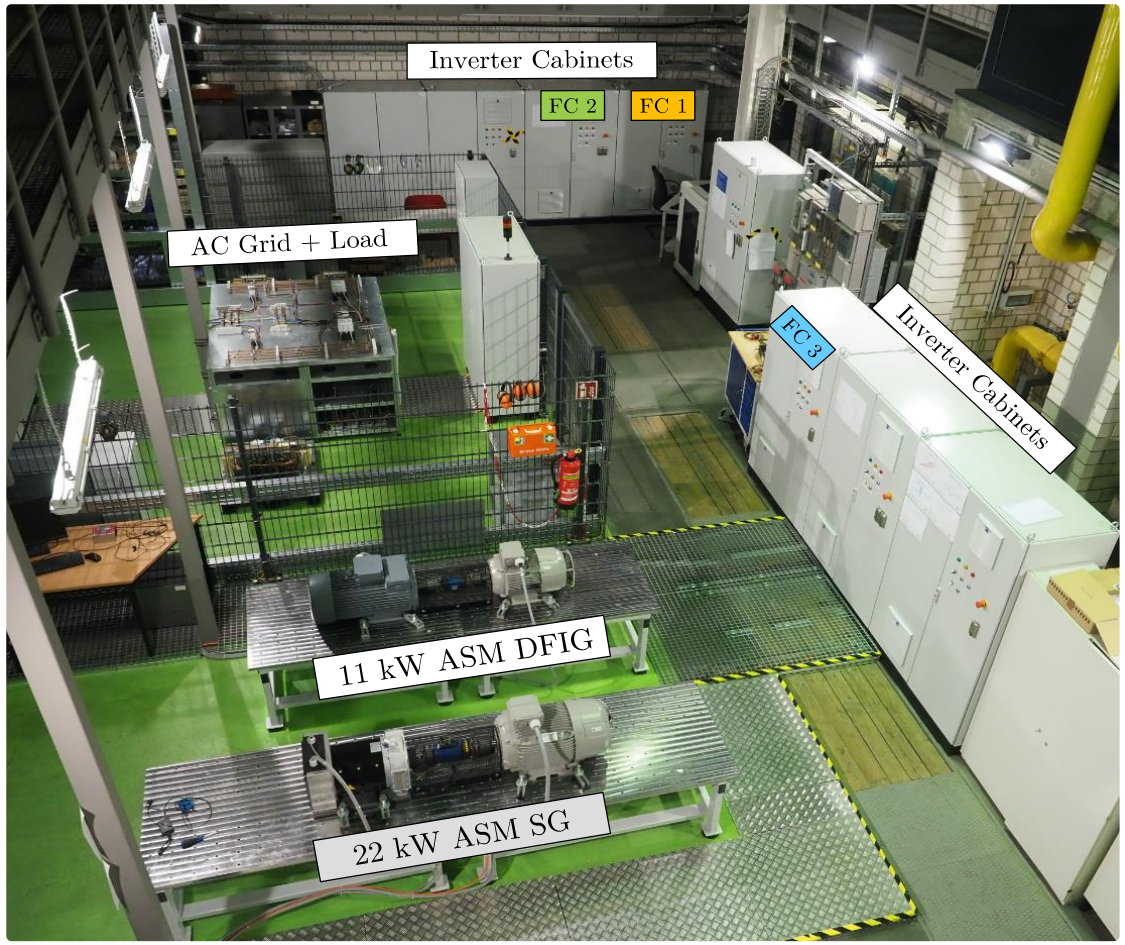


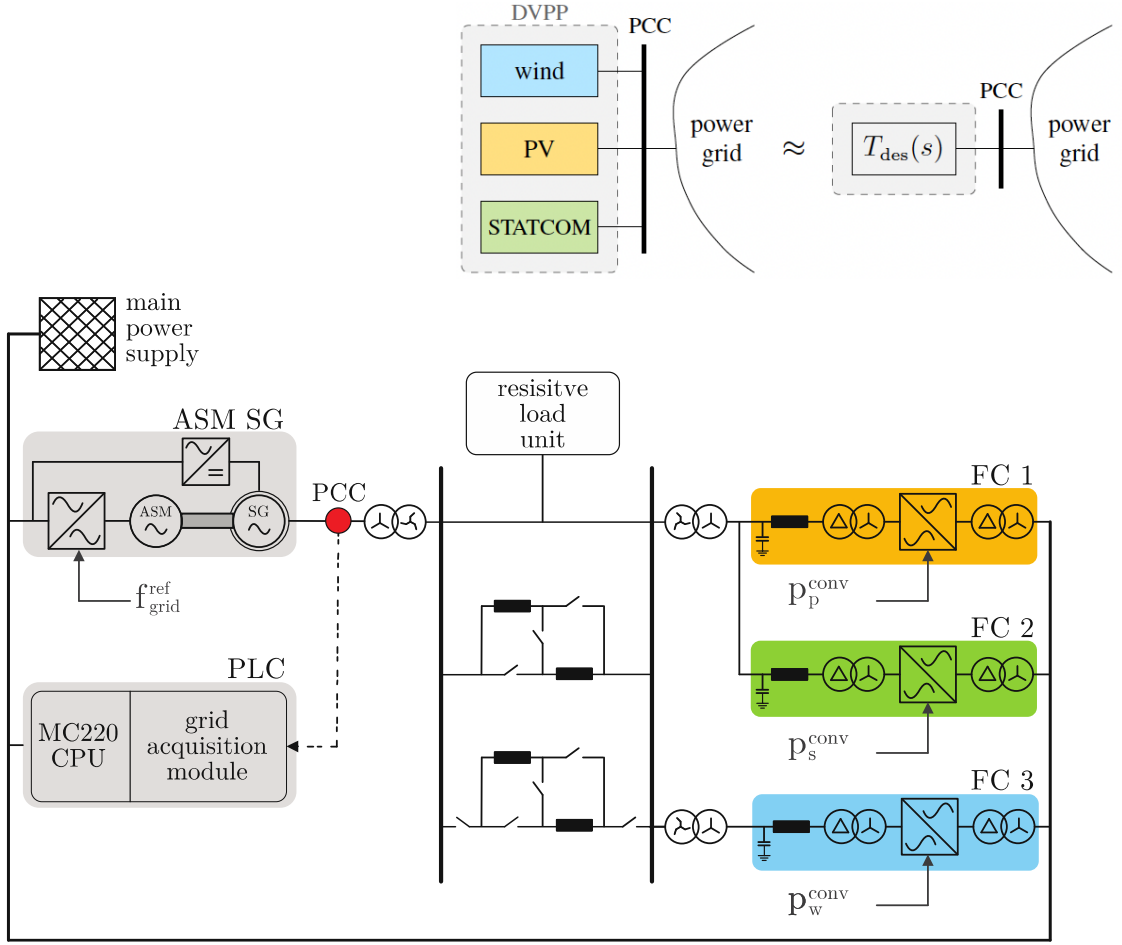




5. Experimental Consideration on HTW Test bed System

Validation using Power Hardware-in-the-Loop Test Bench





5. Experimental Consideration on HTW Test bed System

- **Two Case Studies of Frequency Control**

CASE STUDY I (High Inertia Grid)

- Investigating DVPP behavior during long-term changes in the grid-frequency
- Employing ± 200 mHz grid frequency jump by adjusting reference value of synchronous generator
- Synchronous Generator dynamics dominates the overall grid dynamics (standard PI mode)

CASE STUDY II (Low Inertia Grid)

- Investigating DVPP behavior during short-term changes in the grid-frequency
- Employing a ± 1 kW load jump by adjusting reference value of the restive load container
- Synchronous generator toned down to reduce impact on overall grid dynamics (slow PI mode)

5. Experimental Consideration on HTW Test bed System

Case Study I

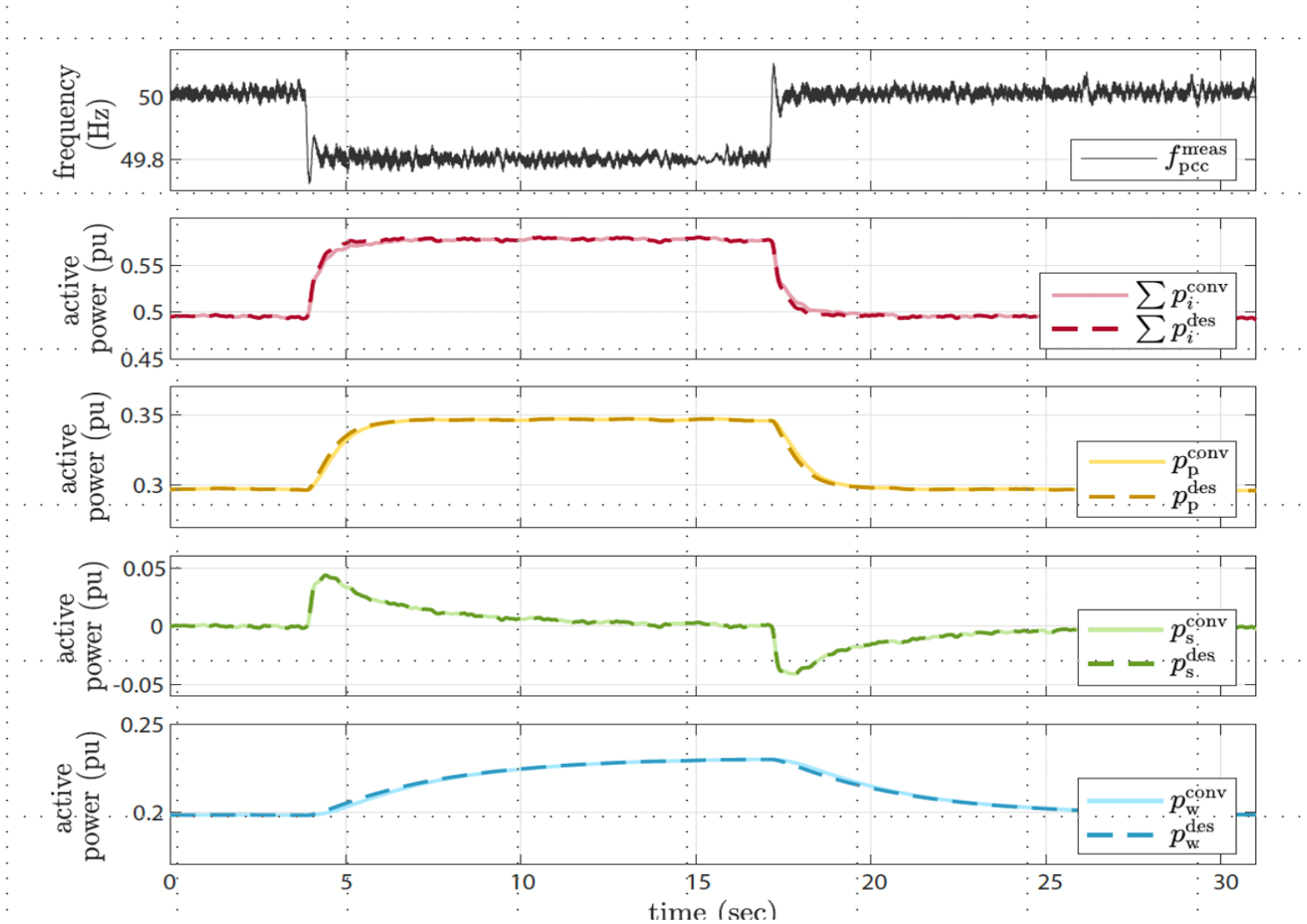
grid frequency

total power of DVPP

power PV plant

power STATCOM

power wind farm



5. Experimental Consideration on HTW Test bed System

Case Study II

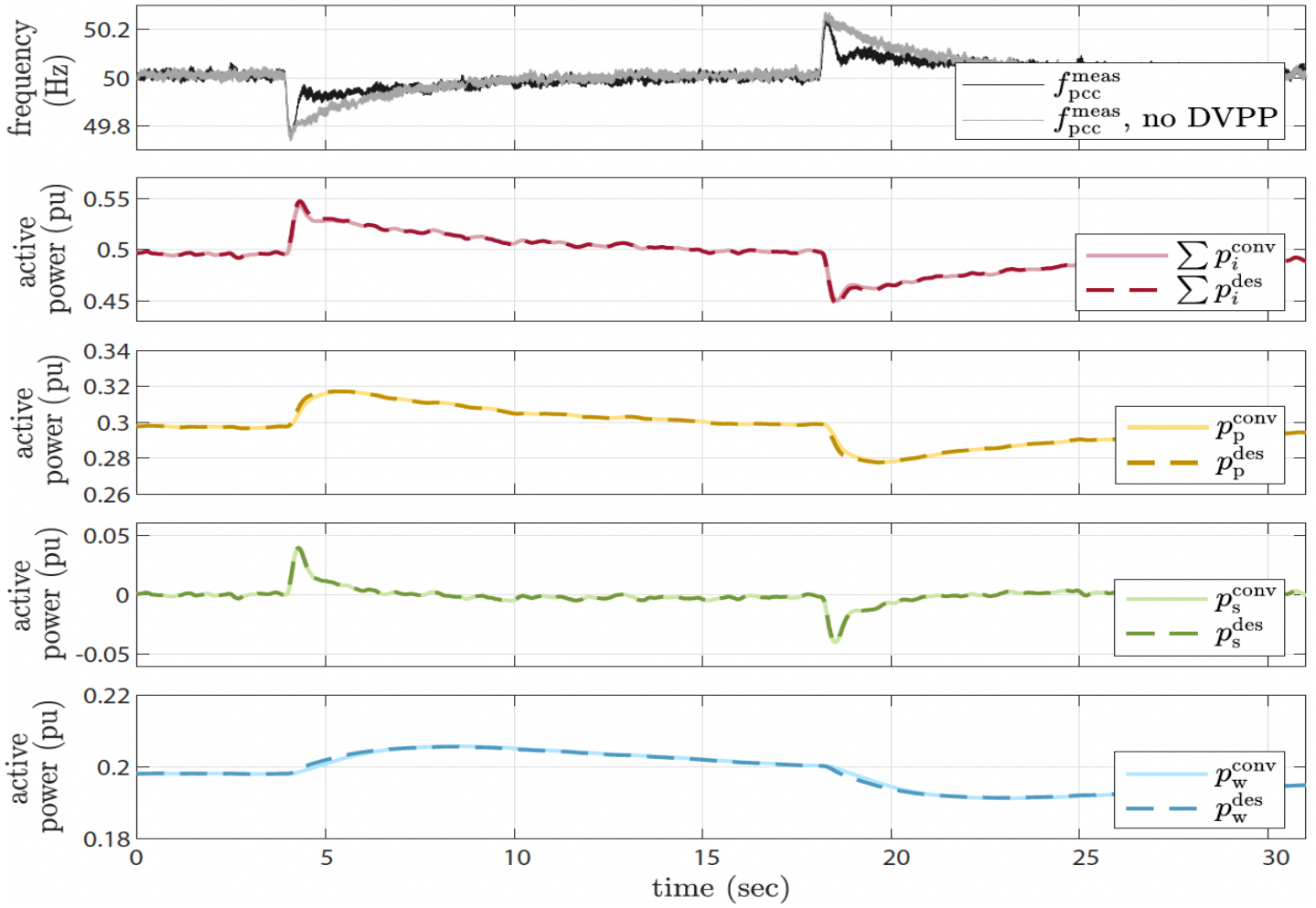
grid frequency

total power of DVPP

power PV plant

power STATCOM

power wind farm



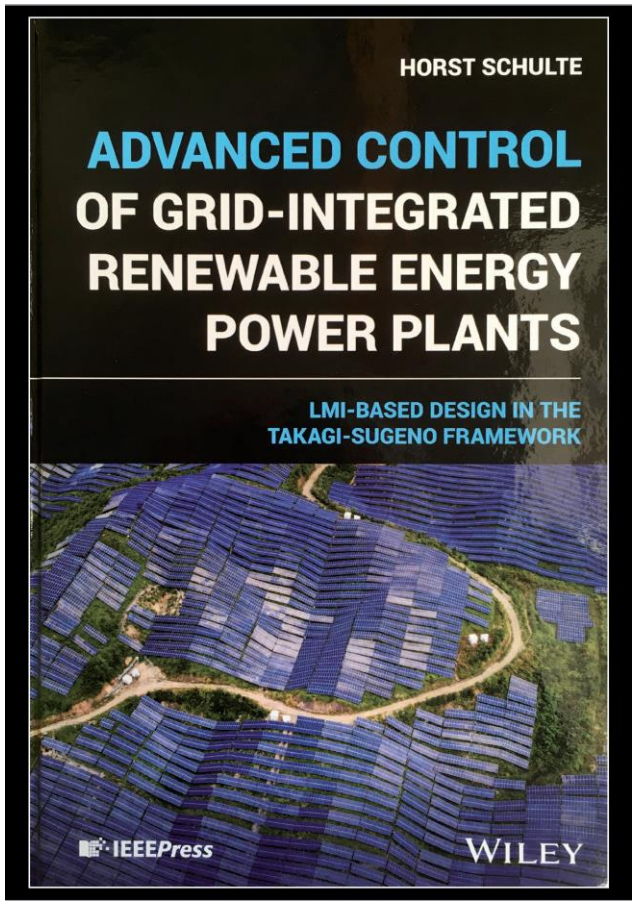
6. Conclusion

- Cascaded Model Reference Control Concept for DVPPs was introduced: Aggregation, Disaggregation, Local Reference models
- Local Model Reference Controller Design by means of Photovoltaic and Wind Power Plants
- Controller Validation in Simulation (Local) and in a PHIL test bench (global)
- DVPP provides FFC and FCR during grid-frequency changes and load variations

7. Literature

Generic Models and Control of Wind Power and Solar Photovoltaic Systems

Schulte, Horst: ***Advanced Control of Grid-Integrated Renewable Energy Power Plants***,
John Wiley & Sons 2024, IEEE Press Series



7. Literature

Local Model Reference Generator Control: Wind Power Plants

- Brunner, Johannes Dieter; Pöschke, Florian; Fortmann, Jens; Klaes, Norbert; Schulte, Horst: ***Analytical Wind Turbine Model for Assessment of Structure-grid Interaction in Grid-forming Mode***. In: Proc. of 24th International Wind & Solar Integration Workshop (WIW2025). Berlin: 2025

- Brunner, Johannes; Fortmann, Jens; Schulte, Horst: ***Model Reference Control for Wind Turbine Systems in Full Load Region based on Takagi-Sugeno Fuzzy Systems***. In: Proceedings MMAR 2024, International Conference on Methods and Models in Automation and Robotics. Międzyzdroje, Poland: IEEE Xplore 2024

- Brunner, Johannes; Schulte, Horst: ***Takagi-Sugeno based Model Reference Control for Wind Turbine Systems in Frequency Containment Scenarios***. In: at - Automatisierungstechnik 73, 10, 2025

7. Literature

Local Model Reference Generator Control: Solar Photovoltaic Systems

- Schulte, Horst: ***Takagi-Sugeno Model Reference Control of Photovoltaic Power Plants to Provide Instantaneous Reserve***. In: Proceedings of IEEE International Conference on Fuzzy Systems 2025 (FUZZ-IEEE). Reims, France: IEEE Xplore 2025

- Schulte, Horst; Kusche, Stephan: ***Fast power tracking control of PV power plants for frequency support***. In: at - Automatisierungstechnik 71, 10, 2023

7. Literature

Global Grid Integration and Services for FFR and FCR by DVPP

- Schulte, Horst; Fortmann, Jens; Brunner, Johannes Dieter: ***Formal Grid Integration of Photovoltaic and Wind Power using Model Reference Control Approach***. In: IET Conference Proceedings of 23rd Wind & Solar Integration Workshop (WIW2024)) . Helsinki, Finland: 2024

- Schulte, Horst; Resener, Mariana: ***Integration of Active Power-controlled Photovoltaic Energy Sources in Distribution Grids by Dynamic Virtual Power Plants***. In: Proc. of 24th International Wind & Solar Integration Workshop (WIW2025). Berlin: 2025

Adaptive Model Reference Control

- Schulte, Horst; ***Adaptive Model Reference Control for Multivariable Takagi-Sugeno Fuzzy Systems***, In: Proceedings 34. Workshop Computational Intelligence. Karlsruhe, Germany: KIT Scientific Publishing 2025